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The influence of stride-length on plantar foot-pressures and joint moments

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ABSTRACT

Purpose: Joint moments have been acknowledged as key factors in understanding gait abnormalities. Gait velocity is further known to affect joint moments and foot pressures. Keeping gait velocity constant is thus a strategy to cancel out the influence of different preferred gait speed between groups. But even if gait velocity is controlled, individuals can choose different stride length–stride frequency combinations to cope with an imposed gait velocity.
Scope: To understand the influence of stride frequency–stride length on joint moments and plantar pressures.
Methods: Twenty healthy young adults had to cross an 8 m walkway with a walking speed of 1.3 m s^{-1}. The wooden walkway was equipped with a force and a pressure platform. While walking speed was kept constant each participant walked with five different imposed stride lengths (SL): preferred (SL0); with a decrease of 10% (SL − 10); with a decrease of 20% (SL − 20); with an increase of 10% (SL + 10) and with an increase of 20% (SF + 20).
Results: Ankle and knee joint moments significantly decreased with a decrease in SL. A significant ($p < .05$) lower peak pressure was achieved with a decreased SL under the heel, toes and midfoot.
Discussion/conclusion: The results showed that a change in stride lengths alters both, joint moments and foot pressures with clinically interesting indications. Redistribution of joint moments in the elderly for example might rather result from decreased SL than from age.

1. Introduction

Adapted and redistributed joint moments are key factors in understanding gait and limited mobility in elderly and chronically diseased people [1–5]. For diabetes, adaptations in joint moment patterns have been associated to adverse plantar pressures, i.e. higher forefoot-to-rear-foot plantar pressure ratio [2]. Gait velocity reputedly affects these parameters [6,7]. Thus, in many studies gait velocity has been kept constant to cancel out the influence of individual, preferred gait speed. Despite this adjustment, individuals can choose different stride length–stride frequency combinations to cope with an imposed gait velocity. Menz et al. [8] reported for the elderly lower gait velocity, characterized by increased cadence and smaller step length (SL), than for younger subjects. DeVita and Hortobagyi[3] reported similar preferred gait velocities for elderly and young subjects, but older subjects presented significantly increased stride frequencies (SF). Monaco et al. [9] controlled leg-length normalized gait velocity in groups with older and younger subjects and reported significantly higher SF for the group of elderly. Individuals with diabetic neuropathy (DN) demonstrated reduced SL [10]. When compared to age-matched controls, they preferred a 20% slower gait velocity, with a reduction of 7% for cadence and 13% for SL [10].

The influence of SL–SF combination on kinetics and kinematics has been poorly documented. Russell et al. [11] investigated the effects of decreased SL, with speed maintained constant (increased SF), on knee joint moments (peak impact shock, peak adduction moment and adduction moment angular impulse) and on metabolic costs. However, no saggital plane kinetics or plantar pressure values have been studied. A 15% decrease in SL significantly decreased the adduction angular impulse, but did not significantly affect two other biomechanical variables which may predispose obese women to knee osteoarthritis (the adduction moment or impact shock). However, an increase in metabolic cost was observed when walking with short, quick steps which may be beneficial for weight reduction or maintenance. Martin and Marsh [27] had ten young adults walk at 1.43 m s^{-1} across a force platform under five SL conditions (preferred SL and SL's that were longer and shorter than those preferred). Contact time, anterior–posterior braking and propulsive force as well as the impulse descriptors and the vertical impulse per

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step augmented systematically as SL increased. Another aspect of SL–SF influence has been studied by Umberger et al. [12] who concluded that the preferred stride rate minimizes the cost of doing mechanical work. However, no kinetic variables have been recorded during these experiments.

As adaptations of spatiotemporal gait characteristics (i.e. SF and SL) are associated with age, diabetes, or obesity, the changes in joint moments and plantar pressures observable in such conditions, might result from the impairment itself or the associated, modified spatiotemporal characteristics. Thus, the isolated influence of SF–SL on joint moments and plantar pressures needs to be investigated to ascertain whether the adapted joint moment and plantar pressure patterns induced by ageing and/or diabetes result from the changed SF, from ageing or from diabetes.

Therefore, this study aimed to investigate the isolated influence of SF–SL on lower extremities' joint moments and plantar pressures at a constant gait velocity.

2. Methods

2.1. Subjects

Twenty healthy subjects were recruited. Participants had to be between 20 and 30 years old; have a body mass index (BMI) between 18 and 25; a leg-length between 80 and 100 cm. The study has been approved by the local ethic committee and all subjects gave written informed consent.

2.2. Material

For gait analysis, five retro reflective markers, located at the trochantor major, lateral epicondyle of the knee, lateral maleolus, calcaneus and the head of the fifth metatarsal detected accelerations of the foot, lower and upper leg. A 2D, 50 Hz video system registered the marker positions in the sagittal plane. The spatial resolution of the video was 3.85 mm $pixel^{-1}$; spatial accuracy of marker position being approximately 25% of this is 1 mm.

A force platform (Kistler® type 9281A, Winterthur, Switzerland), embedded halfway an 8 m-long wooden walkway, recorded ground reaction forces. A pressure platform (EMED-at, Novel GmbH, Munich, Germany), placed on top of the force platform, computed pressure parameters. The pressure platform is as solid as the metal alloy of the force platform, so it does not influence the vector calculation of the force platform itself. The force platform was sampled at 1000 Hz, the pressure platform at 50 Hz.

2.3. Experimental procedure

Subjects' gait was analyzed while crossing the walkway with a pre-defined speed of 1.3 m s^{-1}. Each participant walked at preferred SL (SL0); with a decrease of 10% in SL (SL − 10); with a decrease of 20% in SL (SL − 20); with an increase of 10% in SL (SF + 10) and with an increase of 20% in SL (SF + 20). SF was accordingly adapted to keep speed constant over the five conditions.

Subjects first walked at the predefined speed of 1.3 m s^{-1} at a freely chosen SL across the wooden walkway. A three axial accelerometer (MiniMod, McRoberts, The Haque, NL) on subjects' sacrum determined SF. Two optical gates parallel to the pathway and separated by two meters (at shoulder height) measured the time a subject took to go from one gate to the other. Subjects performed as many trials as necessary to reach the requested gait speed. Once the subject presented the requested speed, the accelerometer-data was used to calculate individuals' preferred SF at the given speed and to derive their preferred step-length. Based on this preferred stride-frequency and stride-length (SL0), SL + 10, SL + 20, SL − 10 and SL − 20, the corresponding SF's were calculated.

The calculated step length was made visible on the course by means of strips of scotch-tape. Rhythm and speed were regulated by a metronome. Participants could thus complete every trial using the accurate SF and SL, ensuring correct landing on the force and pressure platform. The measurements were continued until five trials with a correct foot placement and gait velocity were recorded.

2.4. Data analysis

2.4.1. Preferred SF and stance phase

Gait parameters were derived from a filtered acceleration signal using peak detection algorithms [13]. The average interval between subsequent peaks determined step duration. SF was calculated as the inverse of two times the step duration.

2.4.2. Pressure

Using standard Novel software (Database Medical Professional), both peak plantar pressures and plantar pressure time integrals (PTI) were calculated for the ten commonly used anatomical areas of the foot (Hallux, 2nd toe and 3rd–5th toe, 1st, 2nd, 3rd, 4th and 5th metatarsal head, midfoot, heel) [14].

2.4.3. Joint moments

Based on ground reaction forces, the accelerations of foot, lower and upper leg and the estimated inertial parameters of these segments (based on body mass and segmental length [15]) were calculated. An inverse dynamics approach served to calculate net internal moments of the hip, knee and ankle joints [16]. Maximal plantar flexion moment (AM1), ankle moment at 40% (AM40) of stance phase [2], maximal knee extension moment (KM1) and the maximal knee flexion moment (KM2) were computed from the joint moment patterns during the second half of the stance phase. Maximal hip extension moment (HM1) at initial stance and maximal hip flexion moment (HM2) during the second half of the stance phase [17] were also calculated. The instance during stance phase at which these maximal values occurred was similarly reported. Furthermore, the area under the absolute moment–time curves of "negative" and "positive" joint moments was calculated as it gives an indication of redistribution of work over adjacent joints.

2.5. Statistics

Statistics were performed using SPSS (Version 16.0 for Windows: Chicago, USA). Data were checked for normality. A general linear model for repeated measures ANOVA with stride-frequency as a within-subject factor was performed for each parameter of interest. For maximal ankle plantar flexion moment, maximal knee flexion moment, maximal hip flexion moment, maximal hip extension moment, the absolute time curves of all positive and negative joint moments, the instants of occurrence of peak moments, as well as for all peak pressure and PTI (except peak pressure of front foot), sphericity (Mauchly sphericity test) was violated. Thus, the Huynh–Feldt corrected value was used for data interpretation [18]. Bonferroni post hoc test was performed for pair-wise comparison. A p-value of 0.05 was considered significant.

3. Results

Eighteen participants (11 men and 7 women) with a mean age of 22.4 (2.2) years, mean height of 1.77 (0.09) m and mean BMI of 22.2 (2.0) kg m^{-2} completed the test series. The tests of two persons could not be analyzed due to technical failure.

3.1. Stance phase

Results showed that a decreasing SL (from +20% to −20%) progressively decreased the relative duration of the stance phase ($p < 0.001$). This relative stance duration decreased from just over 70% of the gait cycle in the long stride length condition to 50% of the stride duration in the short SL condition (Table 1).

3.2. Peak pressure

A shorter SL leads in general to lower peak pressure values (Table 2). Peak pressure was significantly influenced under the heel, midfoot and toes ($p < 0.001$). With a decrease of 20% of SL, peak pressure under the heel decreased by about 13%. Peak pressure under the heel increased (36%) while increasing the SL by 20%. The decrease of peak pressure, while decreasing the SL by 20% was approximately −15% under the toes and midfoot.

3.3. PTI

The PTI increased significantly with a longer SL ($p < 0.001$). The increase ranged between 14% (under the metatarsals) to about 27% (under the big toe) of the reference value. A shorter SL decreased the PTI under metatarsals 2–4 by about 20%, under the heel and big toe by more than 60% and under the front foot and toes by around 20%. However, other PTI increased considerably compared to the reference value: under metatarsals 1 and 5 (by 44% and 12%, respectively), under the midfoot (by 225%) and under the 3rd–5th toe (by 128%).

Table 1
The influence of stride length-stride frequency combination on joint moments.

Joint moments mean (SD)	+20%	+10%	SL0	−10%	−20%	p	Post hoc analysis revealed a significant difference between
Min and max joint moments (Nm)							
A_{max}	117.7 (24.7)	117.5 (23.4)	114.9 (24.2)	113.4(23.6)	109.1 (24.5)	0.000	SL − 20 vs SL0, SL + 10, SL + 20, SL − 10
A40	52.8 (15.1)	53.3 (15.0)	53.90 (16.0)	48.6 (18.4)	48.9 (14.7)	0.022	–
KE_{max}	73.0 (20.2)	65.3 (14.9)	61.96 (13.3)	56.8 (12.9)	55.2 (13.9)	0.000	SL0 vs SL + 20, SL − 10, SL − 20 and SL + 10 vs SL − 10, SL − 20 and SL + 20 vs SL − 20
KF_{max}	−5.2 (11.1)	−9.4 (12.9)	−11.65 (11.2)	−9.7 (9.3)	−10.0 (9.7)	0.000	SL0 vs SL + 20
HE_{max}	35.7 (28.3)	33.5 (25.3)	32.45 (21.6)	30.8 (19.4)	33.1 (19.2)	0.418	–
HF_{max}	−28.6 (12.9)	−28.5 (12.5)	−31.60 (11.5)	−39.2 (12.2)	−40.5 (12.2)	0.000	SL − 10 vs SF0, SL + 10, SL + 20 and SL − 20 vs SF0, SL + 10, SL + 20
Relative position in time (%)							
t-pos of A_{max}	78.0 (1.7)	78.4 (1.8)	78.0 (1.9)	78.2 (1.6)	77.7 (2.1)	0.495	–
t-pos of KE_{max}	16.4 (0.6)	17.9 (0.5)	19.3 (0.5)	20.2 (0.5)	19.8 (0.5)	0.000	SL0 vs SL + 20 and SL + 10 vs SL − 20, SL − 20 and SL + 20 vs SL − 10, SL − 20
t-pos of KF_{max}	63.0 (1.2)	65.0 (0.9)	65.7 (0.9)	66.5 (1.2)	65.3 (1.1)	0.540	–
t-pos of HE_{max}	14.2 (0.8)	15.7 (0.7)	16.1 (0.9)	17.1 (1.1)	17.7 (1.2)	0.005	SL + 10 vs SL + 20 and SL + 20 vs SL − 20 and SL − 10 vs SL − 20
t-pos of HF_{max}	86.6 (0.8)	83.4 (0.8)	81.7 (0.6)	81.3 (0.5)	80.1 (0.5)	0.000	SL0 vs SL + 20, SL − 20 and SL + 10 vs SL120, SL − 20 and SL + 20 vs SL − 10, SL − 20
Area under the curves (Nm s)							
Plantar flex. MI	39.9 (10.3)	36.6 (9.5)	33.40 (9.0)	29.7 (8.7)	27.2 (7.7)	0.000	SL0 vs SL + 10, SL + 20, SL − 10, SL − 20 and SL + 10 vs SL + 20, SL − 10,SL − 20 and SL + 20 vs SL − 10, SL − 20 and SL − 10 vs SL − 20
Dorsal flex. MI	0.2 (0.2)	0.1 (0.1)	0.1 (5.1)	0.0 (0.0)	0.0 (0.0)	0.001	SL0 vs SL + 20 and SL + 10 vs SL + 20 and SL + 20 vs SL − 10, SL − 20
Flex. knee joint MI	1.9 (1.7)	2.3 (1.9)	2.26 (1.7)	1.7 (1.1)	1.6 (1.2)	0.000	SL0 vs SL − 20 and SL + 10 vs SL − 20
Ext. knee joint MI	15.2 (5.3)	11.7 (3.9)	10.1 (3.0)	9.2 (2.8)	8.2 (2.7)	0.000	SL0 vs SL + 10, SL + 20, SL − 20 and SL + 10 vs SL + 20, SL − 10,SL − 20 and SL + 20 vs SL − 10,SL − 20 and SL − 10 vs SL − 20
Flex. hip joint MI	7.1 (5.4)	6.0 (4.9)	5.5 (4.2)	5.0 (3.5)	5.2 (3.7)	0.000	SL0 vs SL + 20 and SL + 10 vs SL + 20 and SL + 20 vs SL − 10,SL − 20
Ext. hip joint MI	5.8 (2.5)	5.5 (2.5)	5.6 (2.5)	6.1 (2.1)	5.9 (2.0)	0.553	–
Stance duration (%)	70.8 (4.9)	64.6 (4.8)	59.51 (3.9)	55.26 (3.5)	51.1(3.5)	0.000	All comparison are significant

SL0 = preferred SL; SL + 10 = SL0 + 10%; SL + 20 = SL0 + 20%; SL − 10 = SL0 − 10%; SL − 20 = SL0 − 20%; A_{max} = maximum internal plantar flexion moment; A40 = internal plantar flexion moment at 40% of stance phase; KE_{max} = maximum internal knee extension moment; KF_{max} = maximum internal knee flexion moment; HE_{max} = maximum internal hip extension moment; HF_{max} = maximum internal hip flexion moment; flex = flexor; ext. = extensor; MI = moment impulse.

Table 2
The influence of stride-length-stride frequency combination on plantar pressures.

Plantar pressures mean (SD)	+20%	+10%	SL0	−10%	−20%	*p*	Post hoc analysis revealed a significant difference between
Peak pressure (kPa)							
Heel	551.4 (112.3)	452.4 (92.8)	404.3 (80.8)	359.3 (73.1)	350.7 (50.3)	0.000	All except SL − 10 vs SL − 20
Midfoot	119.9 (35.3)	108.94 (32.2)	116.8 (34.1)	101.6 (33.1)	100.6 (24.1)	0.000	SL0 vs SL − 20
Metatarsalhead 1	282.9 (111.1)	286.56 (145.2)	271.2 (96.9)	270.6 (129.2)	252.9 (104.1)	0.297	–
Metatarsalhead 2	347. 8 (105.7)	352.5 (104.6)	345.6 (90.4)	354.9 (78.0)	343.9 (83.3)	0.703	–
Metatarsalhead 3	343.4 (128.9)	340.8 (118.4)	336.8 (96.8)	358.1 (114.2)	340.8 (101.1)	0.295	–
Metatarsalhead 4	209.8 (67.8)	214.28 (74.5)	213.9 (70.7)	221.3 (63.0)	215.6 (65.4)	0.794	–
Metatarsalhead 5	165.0 (106.7)	157.94 (82.5)	159.3 (97.6)	156.6 (88.1)	162.6 (97.1)	0.913	–
Big toe	496.5 (232.5)	470.6 (220.9)	440.0 (208.2)	398.5 (170.9)	389.1 (177.8)	0.001	SL + 10 vs SL − 20 and SL + 20 vs SL − 10, SL − 20
2nd toe	206. 8 (101.9)	184.9 (80.4)	181.4 (88.9)	148.6 (67.2)	144.6 (81.7)	0.000	SL0 vs SL − 10 and SL + 10 vs SL − 10, SL − 20 and SL + 20 vs SL − 10, SL − 20
3rd–5th toe	180.8 (60.6)	157.8 (57.9)	161.1 (66.4)	122.3 (47.3)	127.6 (65.1)	0.000	SL0 vs SL − 10, SL − 20 and SL + 10 vs SL + 20, SL − 10, SL − 20 and SL + 20 vs SL − 10, SL − 20
Pressure time integrals (PTI)							
Heel	3.6 (0.9)	3.3 (0.8)	3.0 (0.7)	1.1 (0.4)	0.9 (0.3)	0.000	SL0 vs SL + 10, SL + 20 and SL + 10 vs SL + 20, SL − 20 and SL + 20 vs SL − 10, SL − 20
Midfoot	1.1 (0.4)	1 (0.3)	1.0 (0.4)	4.0 (1.4)	3.1 (1.2)	0.000	SL + 10 vs SL − 20, SL − 10 and SL + 20 vs SL − 10, SL − 20 and SL − 10 vs SL + 10, SL + 20
Metatarsalhead 1	4.0 (1.4)	3.9 (1.5)	3.4 (1.1)	5.9 (1.2)	4.9 (0.7)	0.000	SL0 vs SL − 10, SL − 20 and SL + 10 vs SL − 10, SL − 20 and SL + 20 vs SL − 20
Metatarsalhead 2	5.9 (1.2)	5.6 (1.1)	5.2 (0.9)	5.5 (1.1)	4.6 (0.9)	0.000	SL0 vs SL + 10, SL + 20, SL − 20 and SL ± 10 vs SL − 10,SL − 20 and SL + 20 vs SL − 10, SL − 20 and SL − 10 vs SL − 20
Metatarsalhead 3	5.5 (1.1)	5.2 (1.2)	4.8 (0.9)	4.0 (1.1)	3.3 (0.9)	0.000	SL0 vs SL + 20, SL − 20 and SL + 10 vs SL − 10, SL − 20, SL + 20 vs SL − 10,SL − 20 and SL − 10 vs SL − 20
Metatarsalhead 4	4.0 (1.1)	3.7 (1.1)	3.5 (1.2)	2.8 (1.2)	2.3 (1.0)	0.000	SL0 vs SL − 20 and SL + 10 vs SL − 10, SL − 20 and SL + 20 vs SL − 10, SL − 20
Metatarsalhead 5	2.8 (1.2)	2.5 (1.0)	2.4 (1.2)	4.3 (1.7)	2.7 (1.2)	0.000	SL + 10 vs SL − 20 and SL + 20 vs SL − 10, SL − 20
Big toe	4.3 (1.7)	3.8 (1.6)	3.4 (1.5)	2.0 (1.1)	1.3 (0.7)	0.000	SL0 vs SL + 20, SL − 10, SL − 20 and SL + 10 vs SL − 10, SL − 20 and SL + 20 vs SL − 10, SL − 20 and SL − 20 vs SL − 10
2nd toe	2.0 (1.1)	1.8 (0.9)	1.7 (1.0)	1.4 (0.7)	0.9 (0.3)	0.000	SL0 vs SL + 10, SL + 20, SL − 10 and SL + 10 vs SL + 20, SL − 10, SL − 20 and SL + 20 vs SL − 10, SL − 20
3rd–5th toe	1.4 (0.7)	1.2 (0.6)	1.2 (0.7)	2.9 (0.7)	3.1 (1.2)	0.000	SL0 vs SL − 10,SL − 20 and SL + 10 vs SL + 20, SL − 10, SL − 20 and SL + 20 vs SL − 10, SL − 20

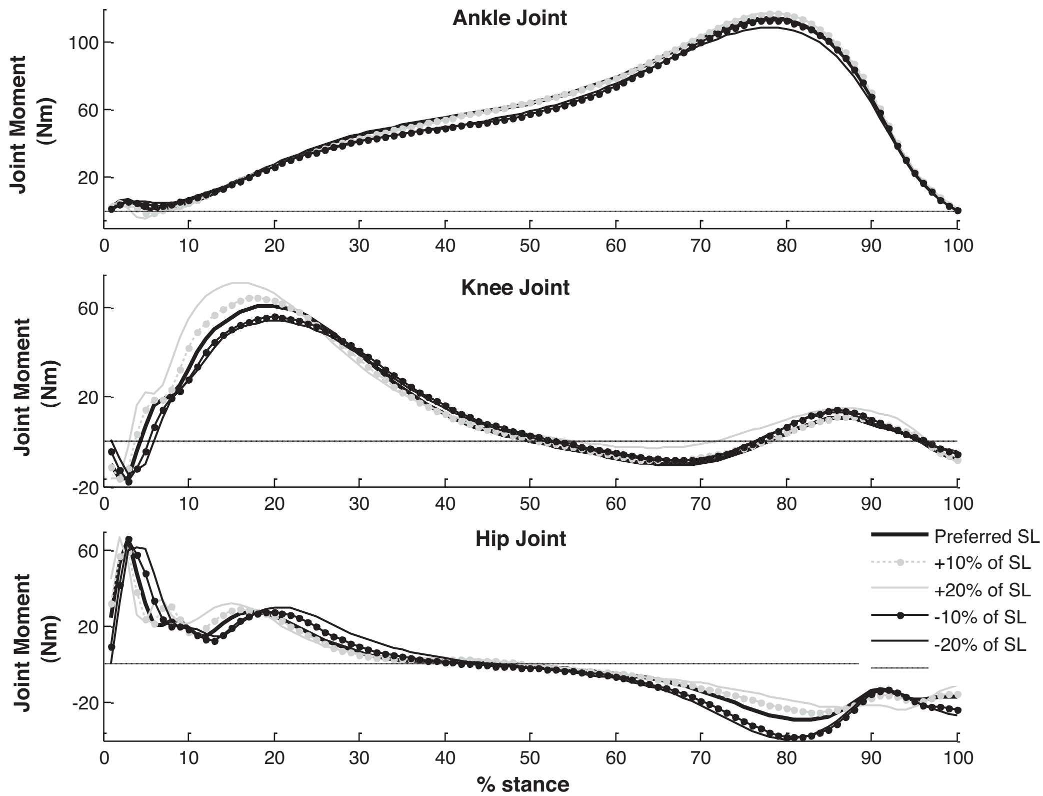

Fig. 1. Sagittal plane joint moments for ankle (upper panel), knee (middle panel) and hip joint (lower panel). Joint moments are presented as a function of stance duration. Positive joint moments represent plantar flexion, knee joint extension and hip joint extension, respectively. The bold lines represent the preferred stride length, the dotted grey line the +10% stride length condition, the solid grey line the +20% stride length condition, the dotted black line the −10% stride length condition and the solid black line the −20% stride length condition.

3.4. Maximum joint moments during walking

All joint moments except the maximal hip extension moment were significantly influenced ($p < 0.05$) by SL (Table 1). The ankle plantar flexion moment at the 40% of stance phase decreased by about 10% and, the maximal ankle moment by about 5% while decreasing the SL. The maximum knee flexion moment was maximal at participants' preferred SL. A significant change was observed only between the reference value and the SL + 20 condition (18%). The maximum hip flexion moment increased by 28% (with −20SL) and decreased by 10% (with SL + 20).

3.5. Timing of joint moments

The instants at which these maximum joint moments occurred were significantly influenced ($p < 0.05$) by the SL for maximum knee extension and hip extension moment as well as for maximum hip flexion moment.

3.6. Absolute joint moment impulses

Manipulating SL affected significantly ($p < 0.05$) all internal joint moment impulses, except for the internal extension hip moment impulse. The absolute joint moment impulses decreased with decreasing SL (between 4 and 40% depending on the joint moment impulse).

4. Discussion

This study aimed to explore the influence of SL on joint moments and plantar foot pressure in healthy gait. The results showed altered joint moments and foot pressure patterns with manipulated SL.

The knee extension and hip flexion moments were especially susceptible to SL variations (Fig. 1). With decreasing SL, the knee extension moment decreased whereas the hip flexion moment increased. The timing of peak joint moments was affected by SL for knee extension and hip flexion. The peak knee extension moment occurred earlier if SL was increased, peak hip flexion moment occurred later with decreased SL. The area under the curve, representing joint moment impulses, was again affected for knee extension and hip flexion, as well as ankle plantar flexion. All three impulses increased with increasing SL.

Less effort per stride with decreasing SL might have been expected, and thus reduced joint moments with decreasing SL. The impulse moments of the respective joints confirmed this expectation. During the first half of the stance phase, the knee extension impulse decreased as SL decreased; during the second half, hip flexion impulse and ankle plantar flexion impulse decreased with shorter SL. The smaller knee extension impulse was realized by reduced maximal knee moment. The reduced hip flexion impulse occurred with a higher maximal hip flexion moment and an obviously later onset of rise of the hip flexion moment (Fig. 1; not analyzed). The reduced plantar flexion impulse tended to be realized by a somewhat lower ankle moment during the whole stance phase.

With decreasing SL, the maximal plantar flexion moment decreased and maximal hip flexion moment increased. This redistribution from ankle joint moment to hip moment has been previously noticed by DeVita and Hortobagyi [3] in elderly compared to younger study participants. Both groups in that study were allowed to walk at a preferred gait velocity. Although the two chose similar velocities, the elderly preferred higher cadence and shorter SL's compared to the younger participants. Monaco et al. [9] studied kinematic and kinetic patterns in nine young and eight elderly healthy subjects who walked on a treadmill at five normalized speeds. They found increased stride frequencies and smaller strides in elderly, compared to young subjects. The data from the present study suggest that the age-associated joint moment redistribution, as reported by DeVita and Hortobagyi [3] and by Monaco et al. [9] originates from a difference in preferred stride length. In addition, it could be noted that joint moment values in this article were comparable to those recorded in previous studies [2,14,19].

Peak plantar pressures decreased with decreasing SL or remained unaffected (metatarsal regions). The PTI displayed a mixed pattern: in some foot sole areas PTI decreased with decreasing SL (heel, 2nd, 3rd and 4th metatarsals, medial toes), in other areas they remained unaffected or increased (midfoot, 1st metatarsal and lateral toes). Interestingly, the clinically relevant [20,21] forefoot-to-rearfoot pressure ratio (MT2/heel, data not explicitly presented) increased for peak pressures and for PTI with decreasing SL. Thus, if SF was increased and SL decreased, the load of the foot sole shifted from the rearfoot to the forefoot. In previous studies, forward displacement of the loading of the foot sole has been associated with diabetes [2,20,21]. In diabetic neuropathy studies, gait velocity has seldom been controlled [22]. Such studies show that people with DN prefer slower gait, with a slightly more pronounced decrease of SL compared to SF [10,23–26]. Typically, individuals with DN chose a 7% lower cadence and a 13% shorter SL, which suggests that patients do increase SF relatively to SL, and at the same time have a higher forefoot-to-rearfoot ratio. Hence, in DN the higher forefoot-to-rearfoot ratio is associated with a relatively higher SF.

In a previous work [2], we suggested that the relative forward displacement of the plantar pressure pattern in people with DN was caused by redistribution of joint moments (higher plantar flexion moment during midstance and reduced knee extension moment). The present study also found this association between ankle and knee joint moment redistribution and increased forefoot-to-rearfoot ratio for pressure patterns. Although the plantar flexion moment in midstance (AM40) was not affected by SL, the knee extension moment was significantly reduced with decreasing SL. Additionally, forefoot-to-rearfoot pressure ratio decreased with decreasing SL. This supports the idea that joint moment redistribution underlies a forward shift of plantar pressure patterns. For diabetes this study and previous work suggest that the forwardly displaced pressure pattern is caused by muscle weakness affecting SL and joint moments. Studies that control gait velocity and spatiotemporal characteristics in people with diabetes or DN should be performed to understand causality between these concepts.

The analysis above suggests that people susceptible for ulceration should be trained to take larger strides at a lower cadence. However, the total loading of the foot should be taken into account; while walking at a higher SF (shorter SL) more strides are needed to cover a given distance. The loading of a foot sole area is therefore determined by the number of strides and the loading per stride. For the most vulnerable parts of the foot sole (under the 2nd and 3rd metatarsal heads), conclusions with respect to the loading per distance covered depend on the variable considered. The peak pressures under the said areas do not differ between conditions; hence the loading of the foot sole per distance covered is greater in the high frequency condition. However, if the PTI is considered, the highest frequency ought to be preferred, as the considerably lower loading per stride in the high frequency condition, easily compensate the 20% more strides needed to cover a given distance. So far, literature is inconclusive as to the variable that predicts ulceration best, i.e. peak pressures or pressure time integrals. Nevertheless, it should be further evaluated how balance may be affected by such a strategy before providing final recommendation for evidence best practice.

This study only assessed healthy persons. Individuals with different pathologies should be assessed to ascertain whether they react similarly. Gait parameters in a three instead of a two dimensional space could be measured. Speed of 1.3 m s^{-1} can be perceived as fast or slow depending on individuals' height and leg length, therefore future projects should evaluate the influence of SL on different populations and with different walking velocities.

This study is one of the first [11,27] to evaluate the isolated influence of SF–SL on foot pressures and joint moments. The manipulation of SL was found to affect plantar pressures by up to 70% and joint moments by up to 25%. Moreover, this study provides evidence that redistribution of joint moments in the elderly results from decreased SL rather than age. For diabetic gait, the factor SL should be considered to understand reported associations between muscle weakness, joint moment redistributions and forwardly displaced plantar pressure patterns.

5. Conclusions

This study evaluated the influence of SL on joint moments and plantar foot pressure. A change in SL alters both joint moments and foot pressures, with clinically interesting consequences. Patients with different pathologies should now be evaluated before providing final recommendations for clinical decision making.

Conflict of interest

All authors disclose any financial and personal relationship with other people or organizations that could have biased the work.

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